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Modelling Pressure Effects in Boiling Brazed Aluminum Heat Exchangers: A Software Comparison

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ABSTRACT

Brazed aluminum heat exchangers (BAHX) are key cryogenic equipment, but their simulation is sensitive to phase change modelling. This work benchmarks ProSec, CO-ProSec Reaction, and Aspen EDR on an ethylene-chiller BAHX using ethane in thermosiphon mode. ProSec's interpolation scheme of tabulated data is validated against CO-ProSec Reaction's approach that employs a thermodynamic model for the evaluation of thermodynamic and physical properties; an initial 25% pressure drop gap is traced to different void-fraction models (slip vs homogeneous). Against Aspen EDR, default duty/quality are ~15% higher; differences are mainly due to nucleate-boiling treatment and distributor pressure drop modelling. Harmonizing options reduces duty mismatch to ~5%.

Keywords: Energy, Modelling and Simulations, Cryogenics, Brazed Aluminum Heat Exchanger

INTRODUCTION

Brazed Aluminum heat Exchangers (BAHX) are one of the most widely used equipment in various industries. They are a core technology in air separation units, industrial gas processing, natural gas treatment and liquefaction (LNG), petrochemical and refinery services.

BAHX are valued for their high thermal efficiency, low weight, compact footprint and limited routine maintenance requirements. Their outstanding performance derives from an exceptionally large heat-transfer area per unit volume: typically area densities are on the order of 1000-1500 $m^2.m^{-3}$, which is much higher than conventional technologies, such as shell and tubes heat exchangers (40 to 70 $m^2.m^{-3}$). In addition, a single core can accommodate up to twenty streams enabling complex

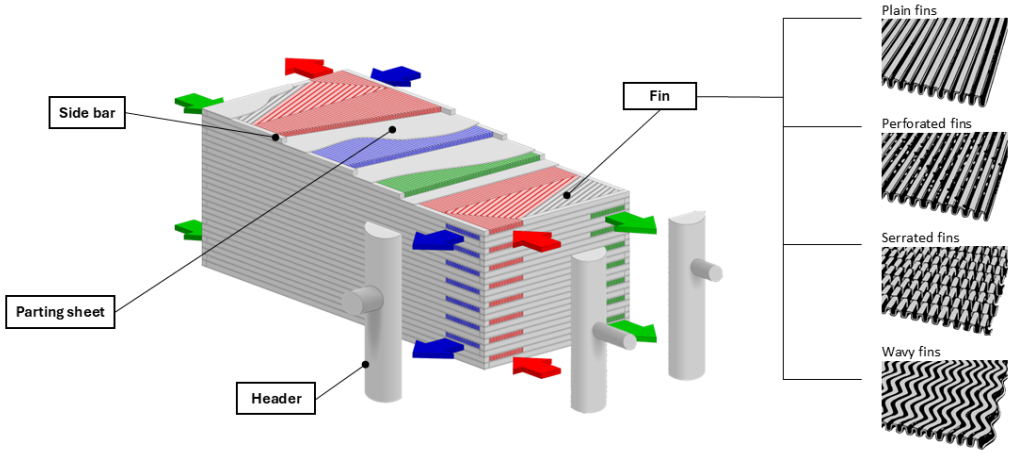

Figure 1. (left) Structure of a Brazed Aluminum Heat Exchanger, (right) Types of fins encountered in BAHX

thermal integration within one exchange and very small temperature approaches(2–5 °C) [1–4].

The geometry of a BAHX core is defined in detail by ALPEMA standards [2]. As schematically shown in **Figure 1**, a BAHX consists of a plate-fin core to which headers are attached. The headers distribute the process streams into the core, where the heat exchange takes place.

The core is built as a stack of passages, ranging from a few tens to more than one hundred layers. Each passage is dedicated to a given stream and comprises: (i) inlet distribution fins (distributors) to spread the incoming flow across the core width, (ii) heat-transfer fin sections where the fluid flows through the exchanger and exchanges heat with adjacent passages above and below, and (iii) side bars (closure bars) that seal the passage and contain the flow as shown in **Figure 2**. Adjacent passages are separated by thin parting sheets, across which passage-to-passage heat transfer occurs

To tailor the heat-transfer performances and pressure-drop behavior, several fin typologies are used beyond the standard straight fins, including perforated fins, serrated fins, and wavy fins.

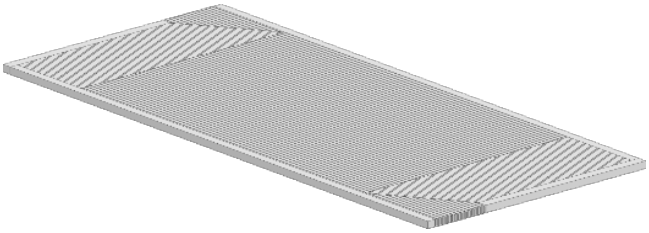

Figure 2. Schematic representation of a single passage

This construction makes BAHX intrinsically multiscale, structurally complex, and strongly heterogeneous, features that underpin their superior performance but also complicate modelling.

Indeed, the same features that make BAHX attractive also make their thermal prediction non-trivial. Strong stream-to-stream coupling, the influence of fin efficiency, axial conduction through parting sheets and side bars, sensitivity to maldistribution and phase change can all affect predicted temperature profiles, pinch locations, and duty. Consequently, selecting an appropriate simulation tool and understanding the modelling assumptions it embeds is essential for credible performance prediction and for robust design and troubleshooting.

To this end, we present a benchmark study comparing three different simulation tools on a representative case with a boiling stream. The first, ProSec, is an in-house software developed at Alfa Laval Golbey in collaboration with Fives ProSim, drawing on more than 30 years of research and industrial know-how. Based on robust numerical methods, ProSec simulate BAHX and analyze local profiles of numerous physical parameters (temperature, pressure, heat transfer coefficient, etc.) and allows the user to fine tune the design of the equipment to reach the best possible performances. It also accounts for pressure effects on thermodynamic properties through a bi-pressure interpolation scheme. The second, CO-ProSec Reaction (version 3.7.8), is a commercial version distributed by Fives ProSim [5]; it evaluates properties directly from thermodynamic models, offering a fully continuous treatment. The third tool, Plate-Fin in Aspen Exchanger Design & Rating (EDR) (version 14) distributed by AspenTech [6], adopts alternative modelling strategies together with its own heat-transfer and pressure-drop correlations . Due to the large diffusion of AspenTech's software in the industrial community, EDR is often the commercial software chosen to simulate heat exchangers. Therefore, comparisons with EDR is a necessary step for validating any development.

The remainder of this paper is organized as follows. Section 1 describes the pressure interpolation method implemented in ProSec. Section 2 introduces the case study used for the software comparison. Section 3 compares ProSec and CO-ProSec Reaction: both tools share the same correlations and numerical resolution framework, but CO-ProSec Reaction evaluates thermodynamic and transport properties from a thermodynamic model via Simulis Thermodynamics through a CAPE-OPEN interface, whereas ProSec relies on tabulated data. This comparison therefore isolates and validates the interpolation strategy. Section 4 presents a critical comparison between ProSec and Aspen EDR, with the objective of identifying the origin of the observed differences and critically discuss them.

PRESSURE INTERPOLATION METHOD

In phase change operation, pressure variations directly govern the saturation temperature and affect vapor quality and enthalpy, thereby influencing the local thermal driving forces. This is important when a thermosiphon stream is present. In a thermosiphon loop, the circulation rate is not imposed by a pump; it results from the balance between the hydrostatic head in the downcomer and the pressure losses across the loop components (downcomer line, BAHX core, and return line).

Figure 3 shows a typical temperature profile for a thermosiphon stream. The fluid enters the BAHX at approximately the saturation temperature at the surface of the liquid in the column. However, due to the hydrostatic pressure in the downcomer, the inlet pressure is higher and the liquid is typically subcooled with respect to the local saturation temperature. The temperature then increases (while static pressure decreases) until the local boiling point is reached, which depends on the pressure profile along the passage. Beyond this point, an evaporation zone develops and the thermodynamic state follows the saturation line as vaporization proceeds [7].

Accurate prediction of pressure drop and pressure-dependent thermodynamic properties is therefore required to reproduce the local thermal profile. This is particularly relevant for BAHX: while aluminum alloys generally retain high tensile strength at cryogenic temperatures compared with carbon steels, they can be relatively susceptible to fatigue damage under cyclic thermal loading [8]. Reliable local temperature profiles are thus important to assess whether significant thermal stresses may occur.

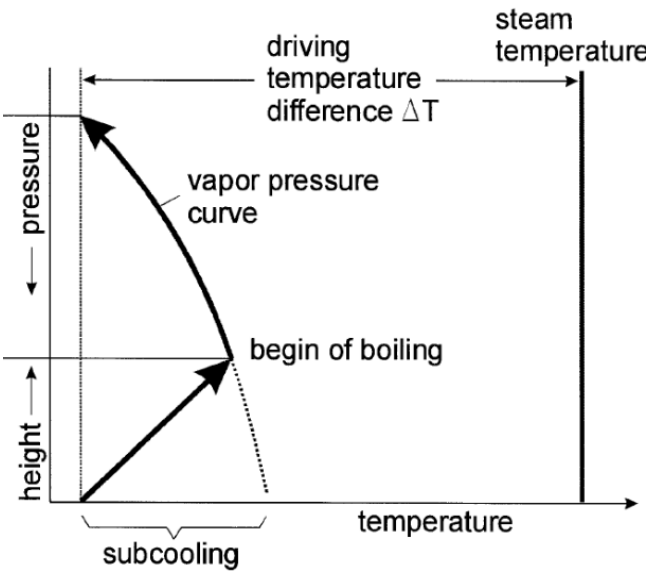

Figure 3. Characterisitic temperature profile for a thermosiphon stream [7]

In ProSec, the user provides for each stream tabulated values of temperature, T, vapor quality, x and enthalpy, h at two pressure levels P_1 and P_2. The program then evaluates the temperature and vapor quality at a specified enthalpy h and pressure P (with $P_1 \leq P \leq P_2$).

This is illustrated in **Figure 4**. In this example, the user provides two enthalpy tables, (T, h_1) and (T, h_2), corresponding to pressures P_1 and P_2. The objective is to determine the temperature $T(h,P)$. First, the interpolation factor r is computed on a logarithmic pressure basis:

$$r = \frac{\ln(P/P_1)}{\ln(P_2/P_1)} \quad (1)$$

The bubble-point and dew-point enthalpies (h_b, h_d) at pressure P are then obtained by interpolation from the corresponding values at P_1 and P_2:

$$h_b = (1-r) \times h_{b_1} + r \times h_{b_2} \quad (2)$$

$$h_d = (1-r) \times h_{d_1} + r \times h_{d_2} \quad (3)$$

Next, the enthalpy h is compared to h_b and h_d to identify the fluid region (liquid, vapor – liquid, or vapor). In the example shown in the figure, $h < h_b$ indicates that the fluid is in the liquid region at pressure P.

Two auxiliary enthalpies h_m and h_n are then defined at P_1 and P_2, respectively, such that the enthalpy shift between them is consistent with the corresponding saturation boundary (i.e, $h_n - h_m = h_{b_2} - h_{b_1}$ in the liquid region). Depending on the region, h_m and h_n are defined as follows:

liquid region:

$$h_m = h - (h_b - h_{b_1}) \quad (4)$$

$$h_n = h + (h_{b_2} - h_b) \quad (5)$$

vapor region:

$$h_m = h - (h_d - h_{d_1}) \quad (6)$$

$$h_n = h + (h_{d_2} - h_d) \quad (7)$$

vapor-liquid region:

$$h_m = h - (1-y)(h_b - h_{b_1}) - y(h_d - h_{d_1}) \quad (8)$$

$$h_n = h + (1-y)(h_{b_2} - h_b) + y(h_{d_2} - h_d) \quad (9)$$

$$y = \frac{h - h_b}{h_d - h_b} \quad (10)$$

Once h_m and h_n are known, the corresponding temperatures $T(h_m, P_1)$ and $T(h_n, P_2)$ are obtained by cubic spline interpolation of the tabulated data at P_1 and P_2. Finally, the temperature $T(h,P)$ is computed as:

$$T(h,P) = (1-r)T(h_m, P_1) + rT(h_n, P_2) \quad (11)$$

The same interpolation approach is used for the vapor quality x. This is only required when the fluid lies in the vapor–liquid region. In the liquid and vapor regions, the vapor quality is simply 0 and 1, respectively.

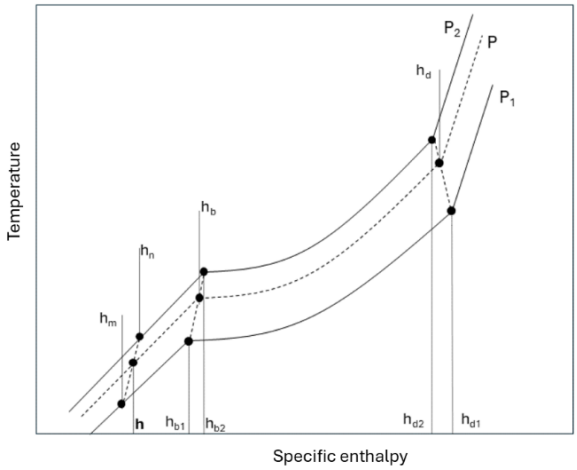

Figure 4: Schematic representation of the interpolation of the temperature between two sets of enthalpic profiles at P_1 and P_2 for a given enthalpy value, h and pressure P in the case of a diphasic mixture

CASE STUDY: ETHYLENE PRODUCTION

Ethylene is a major building block of the chemical industry. It is widely used as a feedstock for plastics, fibers, and other organic chemicals that support key sectors such as packaging, transportation, and construction. Indeed, global ethylene consumption exceeded 150 million tonnes per year in 2017 [9].

Today, ethylene is produced mainly by steam cracking of ethane or naphtha. The overall process is commonly divided into three sections: (i) pyrolysis, where the feed is cracked in furnaces to form light olefins and the effluent is rapidly quenched to limit secondary reactions; (ii) compression and primary treatment, where the cracked gas is cooled, compressed in multiple stages, and purified (notably removal of water and acid gases) prior to cryogenic processing; and (iii) cryogenic product recovery, where chilling trains and distillation towers separate hydrogen/methane and C_2 components, and ultimately split ethylene from ethane, typically at very low temperatures [10].

The case study considered in this paper belongs to the cryogenic recovery section and focuses on ethylene chilling, a duty where BAHX technology is particularly well suited. In the investigated exchanger, an ethylene stream is cooled using ethane as a refrigerant operating in thermosiphon mode. The inlet conditions and operating parameters of both streams are summarized in **Table 1** Thermodynamic properties are evaluated using a Peng–Robinson equation of state coupled with the Soave Boston–Mathias alpha function.

Details of the BAHX internal geometry (core dimensions, stacking arrangement, and fin selection) are proprietary to Alfa Laval Golbey and are therefore not reported here. The exchanger uses in-house fins developed from extensive industrial experience. The corresponding hydraulic and thermal performances - expressed through the Fanning friction factor (C_f) and Colburn factor (C_j) - were characterized experimentally using an internal C_f–C_j test bench, and these measured correlations are used as inputs to the simulations.

Table 1: Details of the streams input data used in the simulation of the BAHX

Parameter	HOT (ethylene)	COLD (ethane)
$\dot{M}$ (kg.h^{-1})	157000	209000
T_{in} (°C)	-24.6	-54.1
P_{in} (bar)	10.44	4.012
Flow Direction	Downward	Upward

COMPARAISON OF PROSEC WITH CO-PROSEC REACTION

Table 2 compares the predicted exchanger performances obtained with ProSec and CO-ProSec Reaction for the thermosiphon stream. Overall, the agreement is very good: the outlet temperatures are virtually identical, and the outlet vapor fraction and exchanged duty differ by about 3%. In contrast, the predicted pressure drop shows a noticeable deviation, up to 25%. This difference is unexpected, since both tools are intended to use the same pressure drop correlations

Table 2: Global performances comparison between ProSec and CO-ProSec Reaction for the thermosiphon stream

Parameter	ProSec	CO-ProSec Reaction
T_{out} (°C)	-53.29	-53.25
x_{out} (kg.kg^{-1})	0.565	0.547
Q (kW)	14490.4	14036.5
DP (mbar)	133.4	106.8

A plausible explanation is the different treatment of properties in the two tools. In ProSec, the influence of pressure on thermodynamic properties (temperature, quality, enthalpy) is accounted for, whereas transport properties (density, viscosity, thermal conductivity, and heat capacity) are interpolated only with respect to temperature. On the other hand, in CO-ProSec Reaction, properties are evaluated directly from the thermodynamic model at each mesh point using the local temperature and pressure. If pressure significantly affects transport properties - particularly density - then the converged pressure drop profile may differ, even when the same correlations are used.

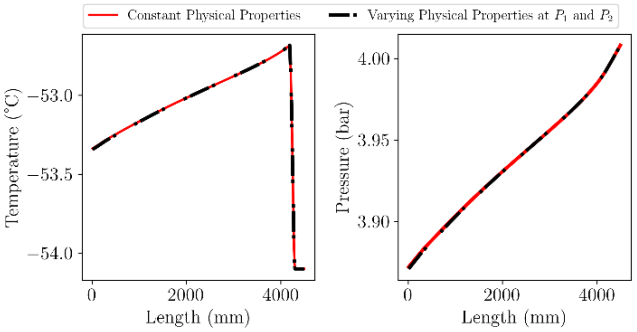

Figure 5: Influence of physical properties variations with respect to pressure on the BAHX performance

To test this hypothesis, an additional simulation was carried out in Aspen EDR, which allows interpolation of both thermodynamic and transport properties with respect to temperature and pressure (the user provides property tables at two pressure levels, and the program performs the interpolation)

Figure 5 compares two Aspen EDR cases. The black

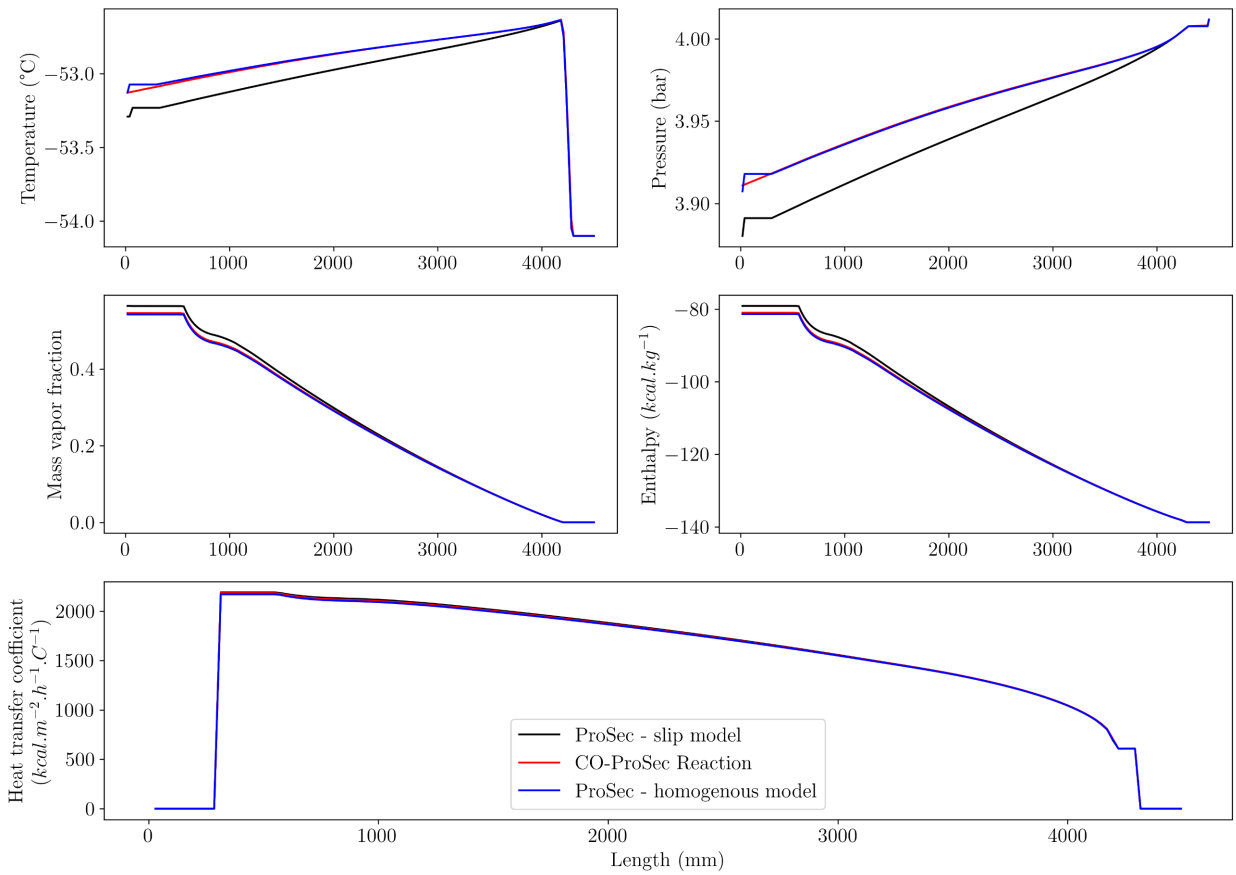

Figure 6: Comparison of the different profiles along the length of the BAHX between ProSec with slip model, CO-ProSec Reaction and ProSec with homogeneous model for the thermosiphon stream

curves correspond to identical transport properties at both pressure levels (mimicking a temperature-only dependence, as in ProSec). The red curves correspond to pressure-dependent transport properties (mimicking the CO-ProSec Reaction approach). In this case, the temperature and pressure profiles overlap, indicating that accounting for pressure dependence of transport properties has no measurable impact on the results. This is consistent with the small overall pressure drop (≈0.1 bar), for which pressure-induced variations of transport properties are expected to be negligible.

These findings indicate that the deviation must originate from another modelling difference between the two tools. To investigate further, the pressure profile was recomputed manually by separating the frictional and static contributions and applying the same frictional and gravitational formulations for both tools. The reconstructed profile matched the ProSec simulation closely, but not the CO-ProSec Reaction results. This pointed to a difference in the treatment of the two-phase static pressure drop.

The key parameter is the void fraction, defined as the volumetric fraction of vapor in the two-phase mixture. Void fraction is required to evaluate two-phase mixture density, and therefore directly affects the gravitational pressure drop [11, 12]. Numerous void-fraction models exist in the literature; they are commonly grouped into homogeneous (no-slip), slip-ratio based, and drift-flux approaches, each relying on different assumptions [12].

In ProSec, void fraction is computed using a slip-based correlation from the HTFS Handbook [13]. In contrast, CO-ProSec Reaction (version used in this study) uses a homogeneous model for void fraction in the computation of the static pressure drop. **Figure 6** compares the profiles along the exchanger length obtained with CO-ProSec Reaction (red curve) and with ProSec using the HTFS correlation (black curve). The pressure profiles show significant differences, which in turn affect the temperature, vapor quality, and enthalpy profiles through the coupling between pressure and saturation conditions in the two-phase region.

When ProSec was configured to use the homogeneous model (blue curve) for void fraction, its results became identical to those of CO-ProSec Reaction as shown in **Figure 6**. This provides strong confidence in the pressure interpolation approach implemented in ProSec: once

the two tools share the same void-fraction treatment, the simulations are consistent. It is also worth noting that since version 3.7.11, CO-ProSec Reaction implements the same void-fraction correlation as ProSec, which is a necessary step to ensure consistent modelling assumptions between the two tools.

This comparison highlights the importance of void-fraction modelling for two-phase flow in BAHX passages. Channel hydraulic diameters typically range from ~1 to 5 mm, whereas many widely used correlations were developed for larger, conventional channels. While two-phase flow in mini-channels has attracted increasing research attention [14, 15], further work is still needed -particularly studies that connect fundamental understanding to industrial geometries and operating conditions - to improve predictive capability in BAHX applications.

COMPARAISON OF PROSEC WITH ASPEN EDR

As noted earlier, comparison with Aspen EDR is essential because it is widely used in industry; benchmarking against it therefore provides a relevant reference point for assessing any simulation approach. Aspen EDR employs its own numerical solution strategy as well as its own set of heat-transfer and pressure-drop correlations.

The first comparison was performed using the default settings in both ProSec and Aspen EDR. This choice is motivated by two practical reasons. First, in typical workflows, Aspen EDR users often rely on the default options for thermal and hydraulic calculations rather than tuning correlation sets or numerical controls. Second, quantifying agreement under default configurations provides a clear baseline from which the dominant sources of divergence can be identified and then reduced in a controlled manner.

As shown in **Table 3**, the default simulations exhibit non-negligible deviations. Aspen EDR predicts a heat duty and outlet vapor quality that are approximately 15% higher than those predicted by ProSec. Aspen EDR also predicts a higher total pressure drop. These differences indicate that the default modelling choices (heat transfer and pressure drop correlations) have a measurable impact on the predicted performance.

To interpret these discrepancies, axial profiles of the cold (boiling) stream - temperature, pressure, vapor quality, enthalpy, and heat-transfer coefficient - were extracted from both simulations and are compared in **Figure 7**. The differences are most apparent in the heat-transfer coefficient: Aspen EDR predicts higher values than ProSec, which directly drives higher local heat flux, a larger enthalpy rise, and therefore a higher outlet vapor quality and duty. This behavior is due to the default correlation choices for the heat transfer coefficient: Aspen EDR uses an HTFS boiling correlation, whereas ProSec uses an in-house boiling correlation (confidential).

Table 3: Comparison of the results of global performances between the different configurations of ProSec and Aspen EDR. See text for the meaning of different case studies

	T_{out} (°C)	x_{out} (kg.kg^{-1})	Q (kW)	DP (mbar)
ProSec - default	-53.29	0.565	14490	133.4
EDR - default	-53.37	0.650	16612	145.8
ProSec – HTFS85	-53.29	0.544	13946	133.3
EDR – NNB	-53.36	0.580	14968	144.9
ProSec - DP	-53.36	0.554	14212	142.3

Differences are also observed in the pressure-drop prediction. Aspen EDR yields a larger pressure drop, which is mainly attributed to the treatment of the distributor pressure drop (see **Figure 7** pressure profile plot for the different zones inside the BAHX). Aspen EDR relies on HTFS handbook methods for distributor pressure drop, while ProSec uses correlations and practices derived from Alfa Laval Golbey's internal experience. A closer look at the pressure-drop breakdown in Aspen EDR indicates that it includes a static contribution in the distributors, whereas this contribution is not accounted for in ProSec. In the Alfa Laval workflow, a more detailed and comprehensive distributor pressure-drop evaluation (including static effects) is performed using a separate proprietary tool, which explains the difference in scope between the two ProSec and Aspen EDR calculations.

ProSec also offers the option to use the HTFS correlation for evaluating the heat-transfer coefficient. In practice, this option is mainly applied to condensing streams, as internal experience indicates that the in-house correlation is better suited to boiling flows. For consistency with Aspen EDR, the HTFS correlation was therefore applied to all streams in ProSec.

Interestingly, this change did not reduce the discrepancy between the two tools but increased it. Under this configuration, Aspen EDR predicts a duty about 20% higher than ProSec, as shown in **Table 3** (ProSec – HTFS85). **Figure 7** explains this trend: in ProSec, switching from the default correlation to HTFS85 reduces the predicted boiling heat-transfer coefficient, which lowers the duty and enlarges the gap with Aspen EDR.

Further examination of Aspen EDR documentation gave more information about the default correlation. In Aspen EDR, the default boiling model includes an additional nucleate boiling contribution to the overall heat transfer coefficient, whereas the HTFS correlation used in ProSec accounts essentially for the convective component only. In boiling flow inside channels, heat transfer is commonly described as the combination of convective

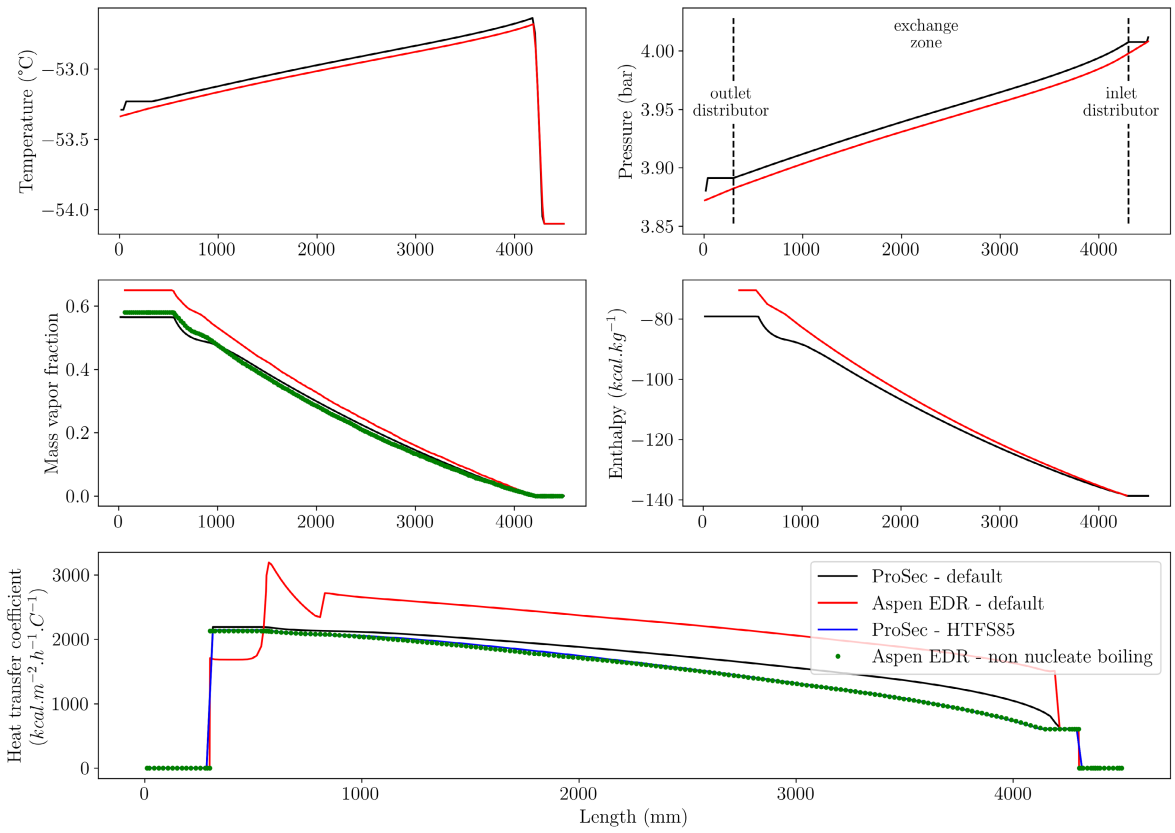

Figure 7. Comparison of the different profiles along the length of the BAHX between ProSec and Aspen EDR under their default settings for the thermosiphon stream. "PoSec – HTFS85" represents Prosec when using the HTFS correlation, "Aspen EDR – non nucleate boiling" is when the option of nucleate boiling is deactivated in Aspen EDR.

boiling and nucleate boiling, with their relative importance depending on heat flux, wall superheat, flow regime, and vapor quality. Nucleate boiling tends to be most influential at low to moderate qualities and sufficiently high wall superheat, while convective boiling becomes increasingly dominant as quality increases. For further information, interested readers are encouraged to read the following references [16–19].

Aspen EDR provides an option to disable the nucleate boiling contribution and retain only the convective component. The resulting case (EDR–NNB) is also reported in Table 3. When EDR–NNB is compared to ProSec – HTFS85, the duty difference decreases substantially (from ~20% to ~7%). This is also visible in Figure 7, where the heat transfer coefficient profiles of EDR – NNB and ProSec – HTFS85 nearly overlap.

To further reduce differences, the ProSec inlet pressure was adjusted so that the pressure at the beginning of the exchange zone matches that in the Aspen EDR simulation (case ProSec – DP). This alignment decreases the remaining gap, yielding a duty difference of about 5% (Table 3). Nevertheless, even when comparable pressure levels and cold-side boiling heat transfer coefficients are obtained, Aspen EDR still predicts a slightly higher duty.

This remaining difference is attributed to the treatment of the condensing hot stream, as shown in Figure 8. The two simulations predict similar heat transfer coefficients over most of the condensation range, except near the onset of condensation. In ProSec, the heat transfer coefficient is linearized between its value at a quality of 0.9 and the single-phase value to avoid numerical instabilities. In Aspen EDR, the two-phase correlation is retained up to the transition to single-phase flow. This reflects different modelling philosophies: ProSec prioritizes numerical robustness in the vicinity of phase-boundary transitions, where certain correlations can become ill-conditioned, whereas Aspen EDR maintains the two-phase correlation closer to the single-phase limit.

Overall, this alignment of modelling options shows that most of the initial discrepancies between ProSec and Aspen EDR can be traced to identifiable assumptions. Once these elements are harmonized, the two tools provide comparable trends and global performances.

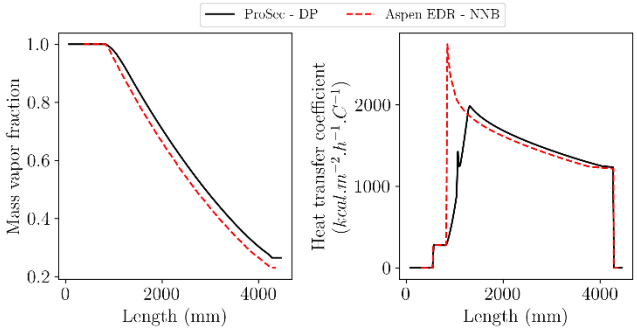

Figure 8: Mass vapor fraction and heat transfer coefficient profiles of the hot stream for both ProSec – DP and Aspen EDR – NNB simulations.

CONCLUSION

This paper presented a benchmark of three BAHX simulation tools (ProSec, CO-ProSec Reaction and Aspen EDR) on a thermosiphon boiling case. ProSec's pressure-interpolation approach was validated against CO-ProSec Reaction; the initial 25% pressure-drop discrepancy was traced to different void-fraction models for the static two-phase contribution (slip model in ProSec versus homogeneous in CO-ProSec Reaction) and disappeared once the same model was used.

Comparison with Aspen EDR showed larger default deviations (≈15% higher duty and outlet quality, and higher pressure drop), mainly due to differences in boiling heat transfer modelling (nucleate contribution included by default in EDR) and in the treatment of distributor pressure drop. When nucleate boiling was disabled in EDR and pressures were aligned at the exchange-zone inlet, agreement improved to within ~5%, with remaining differences linked to condensation modelling near phase-boundary transitions.

Overall, the results emphasize that comparisons between BAHX simulation tools are only meaningful when the main physical assumptions are made consistent. More broadly, the work highlights the need for continued refinement and validation of two-phase correlations in BAHX passages with millimetric hydraulic diameters, where correlation choice can materially affect predicted performance and engineering conclusions.

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